Air pollution control : an economic analysis of a Montana smelter's SO2 emissions

by Edward Barry Asmus

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Agricultural Economics
Montana State University

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The household damage costs are estimated using local weather data in a computer program along with local population and housing data, and the value data from a St. Louis property value study by Ronald Ridker. Agricultural damages from SO2 are found using a methodology to estimate pollution concentration, the absorption rate of the plant, and the duration of fumigation. By combining the estimates of pollution costs with control costs estimated by the Environmental Protection Agency and E. Van Dornick, the total cost equation is written and the minimum point is found which indicates the most efficient level of emission control under the basic assumptions and alternative assumptions using sensitivity analysis.

The analysis indicates that zero emission control is optimal for the smelter studied. Although significant damages are estimated, the high costs of control relative to estimated damages would indicate that zero control is socially efficient.

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Approved:

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ABSTRACT

This paper presents a model which is capable of estimating efficient emission control levels for a particular smelter and which can be adapted to other emitters and other pollutants. The focus of the analysis is the development and use of a methodology to empirically estimate the damage costs of sulfur dioxide pollution.

The household damage costs are estimated using local weather data in a computer program along with local population and housing data, and the value data from a St. Louis property value study by Ronald Ridker. Agricultural damages from SO_2 are found using a methodology to estimate pollution concentration, the absorption rate of the plant, and the duration of fumigation. By combining the estimates of pollution costs with control costs estimated by the Environmental Protection Agency and E. Van Dornick, the total cost equation is written and the minimum point is found which indicates the most efficient level of emission control under the basic assumptions and alternative assumptions using sensitivity analysis.

The analysis indicates that zero emission control is optimal for the smelter studied. Although significant damages are estimated, the high costs of control relative to estimated damages would indicate that zero control is socially efficient.

CHAPTER I

INTRODUCTION

Air, the thin envelope of gases and particles surrounding the earth, is a resource whose quantity and quality play a significant role in determining man's economic, social, and esthetic well-being. Used as a sewer, the atmosphere has varying capabilities for waste disposal. If pollution emitters discharge their wastes with little cost to themselves, the quality of the atmosphere will deteriorate. This creates a problem that demands increased attention.

In order to minimize society's problem, both the costs of pollution control and the cost of pollution damage must be specified. As the following passages note, specifying these costs become a necessary first step in making good pollution control decisions.

> We must have a description of the damage per unit of each object affected as a function of the intensity of air pollution, all other factors that could cause such damage being held constant [48,p.15].

> In sum, the positive and negative values (costs) associated with external effects on environmental quality are ordinarily difficult to gauge and some can never be measured with precision. Nevertheless, there are opportunities for research which should yield information useful for more rational and effective management of environmental quality [26,p.88].

> Without benefit-cost calculations, we cannot determine the desirable amount of abatement [20,p.102].

> The process of proceeding from criteria to clean air, which might be termed air management, might be divided into the various steps: 1. Determine the [economic] effects of various pollutant concentrations and exposure durations on people, animals, plants, and property [33,p.214].

> Everything worthwhile has a cost. Whenever you think you are getting something for nothing, look again - someone, somewhere, somehow is paying for it. . . . The task of ecological economics is to figure out how to restructure the economic system so that these hidden costs will be brought out into the open, with the ultimate aim that no one who benefits from the use of the environment will be able to escape without paying in full [15,p.14].

> It is the lack of information (on the costs of pollution) that is the crux of the matter. . . . I think you will agree that there is no hope of estimating the welfare damages of pollution by simply asking people what they would pay to avoid them. I don't think they know [13,pp.40,43].

This study represents an attempt to measure some of the individual, property, and agricultural damages from sulfur dioxide pollution in the Helena Valley of Montana, connect these damage costs with the appropriate costs of control, and by answering the what and how questions discussed in elementary economic textbooks, indicate how pollution costs could be minimized.

1. "What" emission levels will minimize costs?
2. "How" can resources be combined most efficiently to attain that level?

Sensitivity analysis will then be used to examine the economic importance of various assumptions about the parametric data. Changing the parameter estimates within the "reasonable range" of each will indicate potential payoffs to narrowing that range of estimates for each parameter by appropriate research subject to interaction effects between parameter levels. It will be demonstrated that without better information on some of these physical and economic parameters, mistakes will occur, the effects of which will vary from minor to extremely costly. The level of these costs will depend on the parameter in question. In this manner, researchers in each area can receive guidance and, in the appropriate instances, support in concrete terms for the contention that a proposed piece of research would be valuable to society.

CHAPTER II

THE LITERATURE ON AIR POLLUTION

General Literature on Air Pollution

Although receiving considerable recent attention, air pollution is an enigma that has plagued man for more than 600 years. Members of the nobility petitioned Edward I concerning coal smoke in London in 1300 A.D. One hundred years later, Henry V passed a regulation restricting the movement of coal into the London area, particularly to reduce air pollution [55].

A paper written in 1661 entitled, "Fumifugium", [17] caused such public concern that the English Parliament appointed numerous committees to appraise and recommend solutions to the problem.

In America, Spanish explorers in the sixteenth century, discovered layers of smoke in the Los Angeles area emanating from Indian campfires. Although not reaching dangerous proportions until 1943 [6], inversion layers have continually plauged the Los Angeles air basin.

Although public awareness was slow in coming, the study of pollution problems and concern for the environment is growing.

The American Public Health Association [4] has recently prepared a Guide to the Appraisal and Control of Air Pollution which includes a general discussion of the effects of air pollution, an estimation of the quantities of pollutants emitted into the atmosphere, meteorological aspects, detection and measurement, and a general appraisal of air pollution problems.

The National Air Pollution Control Association's Abstract Bulletin [39] provides one survey of the research being conducted in this field. The research is categorized into 14 broad subject fields, some of which include:

Emission Sources

The characteristics of specific classes of emission sources including types, rates, and the industries involved.

Control Methods

The operating principles, design, operation, and efficiency of equipment and methods of removing pollutants.

Measurement Methods

The development, testing, and evaluation of pollutant determination methods and equipment.

Effects on Human Health

Medical and epidemiological studies.

Effects on Plants and Livestock

Pollution effects on plants and livestock.

Effects on Materials

Research on the corrosion and deterioration of physical materials, buildings, and structures.

Economic Aspects

Studies that relate and examine pollution damage costs and pollution control costs.

Standards and Criteria

Recommended or adopted guides, criteria, and standards for allowable emission limits or pollutant concentrations, air quality, equipment characteristics, and fuels.

Other periodical guides to the air pollution literature include Air Pollution Titles [3], APCA Abstracts [2], and Air Pollution Abstracts [1].

Important periodicals such as Environmental Pollution, The Journal of the Air Pollution Control Association and Environmental Science and Technology publish an array of papers dealing with air pollution. The Natural Resources Journal and Land Economics specialize in the economics and sociology of environmental control, while papers on the health aspects of air pollution occasionally appear in the American Journal of Public Health and the Archives of Environmental Health.

Hagevick [23] has recently written an excellent book on air pollution control. After a brief introduction examining the pollutants responsible for the current situation, he examines the economic, political, and institutional issues by applying them to a specific airshed. Through case studies of Los Angeles and New York City, a basis is provided for integrating decision-making with the economist's minimum-cost solution (Chapter III of this thesis develops this concept), pointing out the strong as well as the weak decision-making strategies. Before good decisions can be made, estimates of the total damages attributable to air pollution in the airshed at various possible emission levels must be made.

The Report of the Air Conservation Commission resulted in a book entitled, Air Conservation [14]. Authored by 12 leading authorities from many fields of specialization, this book provides a wide ranging view of air pollution, including meteorology, pollutants and their effects, the need for air conservation, pollution control, and the socio-economic factors that accompany air pollution and urban development. Because of its complexity, the authors outline the broad tasks facing the scientific community, including basic and applied research on pollutant interactions, effects, and control. The task of government would be one of supporting the appropriate research, helping gather the necessary information, enforcing pollution decisions, and educating its citizens to create a broad public understanding of the problem.

Economic Literature on Air Pollution

Whenever the welfare of an economic unit (or units) is directly affected by the activities of another, externalities exist. Air pollution represents a classic example of an externality. Because air appears to the emitter as a free resource, it is overused. Overuse reduces efficiency in that receptors suffer more from damages than emitters will save in not having to control their pollution. Overuse affects equity by forcing owners of air rights (unless all rights are owned by emitters) to suffer damages without proper compensation.

Various possible solutions to the externality problem are examined by Coase [10] and Mill [20]. The possibilities include emission taxes, payments based on marginal pollution damages, flexible emission standards, zoned emission standards, prohibition of emissions, factor subsidies, and others. Care must be taken to account for the additional and informational costs associated with each proposed solution.

When external effects cause a misallocation of production, the goal becomes one of accounting for all the benefits and costs flowing from the economic activity being studied.

Treatments of benefit-cost analysis and its application to the micro-economic theory aspects of pollution control can be found in Eckstein [16], Grosse [22], Harberger [25], Herfindahl and Kneese [27], Prest and Turvey [46], Steiner [58], Wilson and Minnotte [74], Zerbe [77], and Stroup [60]. These papers present the elements of a research strategy for conceptualizing the problem, specifying the relationships and variables necessary for making changes in control decisions, and applying empirical information to actual case study situations.

Prest and Turvey's paper is perhaps the most comprehensive survey of benefit-cost literature and it does provide an extensive bibliography. Benefit-cost analysis, these authors note, is a way of setting out the factors which need to be taken into account to make certain economic choices. Questions such as Which costs and which benefits are to be included in the analysis? How are they to be valued? At what interest rate are they to be discounted? and What are the particular constraints applicable to the analysis? are a few of the general principles of benefit-cost analysis that are enumerated.

Wide divergence of opinion exists over the usefulness of benefit-cost analysis. At one extreme is Hall's statement [24,p.173]:

> We have begun to grope our way towards a practical concept of economic planning which may prove in a few years' time to be as revolutionary in its policy implications as was the Keynesian revolution in economics thirty years ago. It also originated, many years ago, with a Cambridge economist: Keynes' contemporary Pigou. It is the concept of social costs and social benefits. . . . This leads to the revolutionary concept that we can actually add up the social costs and benefits, in money terms, by asking what value people would themselves put on them. We can then express them as a rate of return on capital, as an ordinary capitalist would, and so determine our investment rationally, from the point of the community as a whole, just as the capitalist can now do from his private point of view.

Another statement indicating an opposing view is by Smithies [56,pp.344-345], which states:

> The foregoing discussion [on benefit-cost analysis] leads to two major conclusions: First, judgment plays such an important role in the estimation of benefit-cost ratios

> that little significance can be attached to the precise numerical results obtained. . . . Second, competition is likely to drive the agencies towards increasingly optimistic estimates; and far from resolving the organizational difficulties, computation of benefit-cost ratios may in fact make them worse.

Prest and Turvey [46] take a position between the two extremes, recognizing that even if benefit-cost analysis cannot give right answers, it can play the negative role of screening projects and rejecting those answers which are less promising. They argue the case for benefit-cost analysis is strengthened if its limitations are openly recognized and emphasized.

Many of the estimates of the damage costs of smoke and air pollution from the turn of the twentieth century until 1950 can be found in papers by Bennet [7], Flagg [18], Gibson [19], Johnson [31,34], Obermeyer [41], Parsons [43,44,45], Rolleston [50], Shaw and Owens [53], Simon [54,57], Mellon Institute [63,72], Uhlig [75], and the Beaver Committee [21].

Basically, these articles represent rough estimates of the smoke damages suffered by various cities and countries. Annual smoke damages (1939) to Indianapolis, for example, were estimated to be $15 million [31], while Milwaukee suffered $10 million [34]. Simon [57] estimated the annual smoke damages (1946) to Great Britain to be $50 million. S. B. Flagg [18] added an interesting twist to the damage cost estimates cited by other authors. He viewed smoke in terms of damage to emitters, rather than receptors. Because smoke indicates inefficiency in fuel consumption, half-burnt coal, and dividends that should be distributed to stockholders, he called for an improved design of furnaces and mechanical equipment. The incentives for improving "control equipment" would come from a strict enforcement of statutes controlling emissions.

Research in the last decade on the damage costs of air pollution would include Michelson and Tourin [35,36,37], Ridker [48], Ridker and Henning [49], Anderson and Crocker [5], Wilson and Minnotte [74], and Stroup [60].

Michelson and Tourin [37] used questionnaires to estimate the added household expenditures of cleaning resulting from suspended particulates. Although interesting, their study suffers from the problems associated with questionnaire techniques and the difficult question of how to evaluate the damages of pollution which were not paid for in the form of extra cleaning, laundry, painting, etc.

Ridker, in his book, Economic Costs of Air Pollution [48], used a number of approaches in an attempt to measure air pollution damages. In an effort to link the incidence of disease with air pollution, he examined correlations between polluted areas and premature deaths, treatment, and absenteeism. The costs would be the value of medical treatment and foregone income. His study revealed no conclusive evidence using this method. Another approach was one similar to Michelson and Tourin's questionnaire determining soiling costs. By comparing the laundry, dry cleaning, and other costs associated with pollution of different cities, Ridker hoped to capture an amount people actually did pay for living in a polluted area. Here again, the results were indeterminate. Ridker's third approach, and the one whose results are used in this thesis, investigated the differences in property values resulting from polluted versus nonpolluted situations. Using a cross-section study of St. Louis property values, Ridker was able to explain 92 percent of the variation in property values with a regression equation. Using sound econometric analysis, he showed that St. Louis residents were willing to pay about $245 more for a house for each .25 $mgSO_3/100\ cm^2/$ day avoided. Here, a single market price reflects what people were willing to pay to get away from pollution where they lived.

Anderson and Crocker's study of air pollution and residential real estate values also proceeds on the basis that a substantial portion of air pollution damages to artifacts and organisms is capitalized negatively into the value of land. They first develop a qualitative model to determine residential property values which include characteristics of both households and properties as explanatory variables. Basically, they used the postulates of Lancaster's development of consumer behavior theory. Using log linear forms estimated by

Ordinary Least Squares, instead of a linear fit which appeared to be best for Ridker, they showed that marginal property values were reduced from $300 to $700 per property because of pollution.[1] Anderson and Crocker used particulates as an explanatory variable, whereas Ridker reported unsatisfactory results using particulates, and they were critical of Ridker's use of 1960 Census Data coupled with pollution data gathered in 1963 and 1964. This, they argued, could result in biased estimates.

Wilson and Minnotte's study of soiling caused by stationary sources of particulate emissions in the Washington, D. C., area [74] uses benefit-cost analysis to make pollution control recommendations. By combining a diffusion model with Michelson's data on soiling damages, they calculate a benefit figure for each control increment. Costs of control are then subtracted from the calculated benefits, yielding a net benefit calculation for every control level. They conclude that benefit-cost analysis can be used in making emission control decisions, and with better input data can be used to establish emission levels for all types of pollutants. They warn that their model can be used only for illustrative purposes, as it deals with only one type of pollutant and one geographic area.

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[1] Marginal damages refer to an additional 10 $mg/m^3/day$ of suspended particulates plus an additional .1 mg $SO_3/100\ cm^2/day$ of sulfation.

Stroup develops a model [60] which is capable of locating optimal control levels for any number of air pollution sources under the jurisdiction of a control authority. The model is then used to analyze various control strategies, detailing the strengths and weaknesses of each. By applying the model to a particular copper smelter, it is demonstrated that several million dollars in annual damages can be avoided at optimal control strategies. Many developments in this paper are based on Stroup's methodology.

The Literature on Plant Injury by Air Pollutants

Scientific attention was directed to the problem of pollutant injury to plants as far back as 1871, when Stöckhardt [59] wrote about smoke damage to German forests and when Cameron [9] examined the damage to vegetation in London. Research on sulfur dioxide damage to plants in this country began at the turn of the century [64], with Swain [62] reviewing the outstanding periodic developments. Another good review of the effects of pollution damage to plants is Crocker [12] who reviewed much of the early work on sulfur dioxide and other pollutants by the Boyce Thompson Institute. A publication by the National Research Council of Canada [40] examines much of the sulfur dioxide research in connection with smelter injury to plants. Also, an excellent comprehensive review of the entire problem of air pollution effects on vegetation is given by Thomas [64] and updated by him in 1961 [65].

It has been established in the literature [42,66] that sulfur dioxide injury to vegetation follows the relationship

$$(C - C_0)t = K. \tag{2-1}$$

In this equation, C is the concentration of sulfur dioxide (parts per million--ppm) which can cause traces of injury to alfalfa in t hours, and C_0 and K are constants. Under conditions of maximum sensitivity, C_0 was found to be 0.33 and K equalled 0.92. That is, given a concentration of 1.25 ppm, incipient markings can be found on alfalfa in one hour. Notice that a concentration of 0.33 ppm can be endured indefinitely without causing injury.

Thomas and Hill [67] generalized the preceding equation, calculating equations for various amounts of leaf destruction at maximum sensitivity for alfalfa as follows:

$$\begin{aligned} t(C - 0.24) &= 0.94 && \text{Incipient Injury} \\ t(C - 1.4) &= 2.1 && \text{50\% Leaf Destruction} \\ t(C - 2.6) &= 3.2 && \text{100\% Leaf Destruction} \end{aligned} \tag{2-2}$$

From these equations, concentration levels of 1.2, 3.5, and 5.8 ppm would, in one hour, destroy traces, half, or all of the leaf area of the crop, respectively.

The different species of plants vary considerably in their susceptibility to injury by sulfur dioxide. O'Gara worked out factors for about 300 species and varieties of plants, giving their sensitivity relative to alfalfa as unity. These have been published and some are listed in Table I [66].

Environmental factors have a significant effect on predisposing vegetation to SO_2 injury [32,52,66]. Relative humidity is perhaps the most important external factor affecting a plant's susceptibility. High relative humidity favors the opening of the stomata and this allows a high absorption rate of the plant. Soil moisture is another important environmental factor, causing plants to become extremely resistant when moisture approaches the wilting point. When the soil moisture is very low, the leaf stomata tend to close in order to guard against excess transpiration losses. When moisture is adequate for growth, however, variations within wide limits do not appreciably affect susceptibility. The importance of light intensity and its relation to the response of a plant has been assessed differently by various investigators. Swain [62] considers it to be a major factor, while Holmes [29] and Setterstrom [52] believe it to be of minor importance. Considering atmospheric temperature, Swain [61] concludes that a plant is more resistant to sulfur dioxide at temperatures of 5°C and below, with little variation above 5°C. Wells [73] agrees with this basic conclusion.

Brisley and Jones [8], Hill and Thomas [28], Holmes, Franklin, and Gould [29], National Research Council of Canada [40], and Thomas and Hendricks [66] found that reduction in yield is proportional to

TABLE I. RELATIVE SENSITIVITY OF CULTIVATED AND NATIVE PLANTS TO INJURY BY SULFUR DIOXIDE (Determined by O'Gara).

Sensitive		Intermediate		Resistant	
		Cultivated Plants			
Alfalfa	1.0a	Cauliflower	1.6a	Gladiolus (1.1-4.0)b	2.6a
Barley	1.0	Parsley	1.6	Horse-radish	2.6
Endive	1.0	Sugar Beet	1.6	Sweet cherry	2.6
Cotton	1.0	Sweet William	1.6	Canna	2.6
Four o'clock	1.1	Aster	1.6	Rose	2.8-4.3
Cosmos	1.1	Tomato (1.3-1.7)b	1.7	Potato (Irish)	3.0
Rhubarb	1.1	Eggplant	1.7	Castor bean	3.2
Sweet pea	1.1	Parsnip	1.7	Maple	3.3
Radish	1.2	Apple	1.8	Boxelder	3.3
Verbena	1.2	Catalpa	1.9	Wisteria	3.3
Lettuce	1.2	Cabbage	2.0	Mock orange	3.5
Sweet potato	1.2	Hollyhock	2.1	Honeysuckle	3.5
Spinach	1.2	Peas	2.1	Hibiscus	3.7
Bean	1.1-1.5	Gooseberry	2.1	Virginia creeper	3.8
Broccoli	1.3	Zinnia (1.2)b	2.1	Onion	3.8
Brussels sprouts	1.3	Marigold	2.1	Lilac	4.0
Pumpkin	1.3	Hydrangea	2.2	Corn	4.0
Table beet	1.3	Leek	2.2	Cucumber	4.2
Oats	1.3	Begonia	2.2	Gourd	5.2
Bachelor's-button	1.4	Rye (1.0)b	2.3	Chrysanthemum	5.3-7.3
Clover	1.4	Grape	2.2-3.0	Snowball	5.8
Squash (1.1-1.4)b	1.4	Linden	2.3	Celery	6.4
Carrot	1.5	Peach	2.3	Citrus	6.5-6.9
Swiss chard	1.5	Apricot	2.3	Cantaloupe (muskmelon)	7.7
Turnip	1.5	Kale	2.3		
Wheat	1.5	Nasturtium	2.3	Arbor vitae	7.8
		Elm	2.4	Currant blossom	12.0
		Birch	2.4	Live oak	14.0
		Iris	2.4	Privet	15.0
		Plum	2.5	Corn silks and tassels	21.0
		Poplar	2.5		
				Apple blossoms	25.0
				Apple buds	87.0

a/ Factors of relative resistance compared with alfalfa as unity.

b/ More probable factors based on later experience.

the amount of leaf area destroyed. The following equation may then be used when the constants have been determined.

$$Y = a - bX \tag{2-3}$$

where: Y = the yield;

X = the percentage leaf area destroyed;

a = a constant approximately 100 percent; and

b = the slope.

The question frequently arises as to how far conclusions drawn from the results of experimental fumigations under cabinets may be applied to crop plants growing under natural field conditions in a smelter zone. Katz [32,p.2458] found that "the results demonstrated conclusively that the response of crop plants to sulfur dioxide under natural conditions is not essentially different from that found in fumigation experiments under cabinets."

The issue at hand is not just one of specifying effects, but actually determining whether these effects have any economic importance. Regardless of the biochemical mechanisms involved, or the striking damage appearing on colored photographs, the essence of the analysis must be an estimate of the magnitude of losses suffered by society. Chapter III presents a methodology and Chapters V and VI use it to empirically investigate the damages from sulfur dioxide pollution by a specific smelter.

CHAPTER III

AN ECONOMIC PRESENTATION: DIAGRAMMATICAL AND MATHEMATICAL

Dirty air is expensive. Unfortunately, clean air is also expensive. The resulting trade-off is one between the size of control costs and the size of pollution damage costs. These costs are the focus of the following economic analysis and their subsequent measurement the key to sound decisions of control.

The money and prices used to measure these costs are useful as a unit of account and a common denominator. The focus of interest is not on dollars and prices themselves, but rather their role as a yardstick in measuring the problems, opportunities, and choices of people. The price system in a market economy is a system of social accounting which (in the absence of externalities) keeps track of all the benefits and costs of an economic activity.

Diagrammatic

A simplified view of the physical problem is shown in Figure 1, and its resultant economic aspects in Figures 2, 3, and 4.

Pollution (emissions) vented to the atmosphere (transport mechanism) yield levels of ambient air (air quality) which cause some degree of economic losses (damages) as shown in Figure 1.

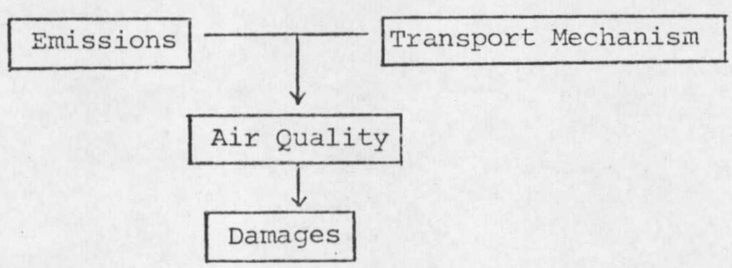

Figure 1.

If society wants a certain standard of air quality maintained, such as point A in Figure 2, control costs of CC_A must be incurred. Given CC_A of control, quantity E_A of emissions would cause DC_A damage costs. Damage costs can then be thought of as a function of emissions (or an air quality standard).

By combining the southeast and southwest quadrants of Figure 2, the damage and control costs of various levels of emissions can be represented by Figure 3. Adding damage costs to control costs yields a total cost curve for varying emission levels pictured in Figure 4. TC_1 and E_1 represent minimum total cost at an optimum level of emissions. At this point, E_1, the marginal costs of control equal the marginal costs of pollution damage.

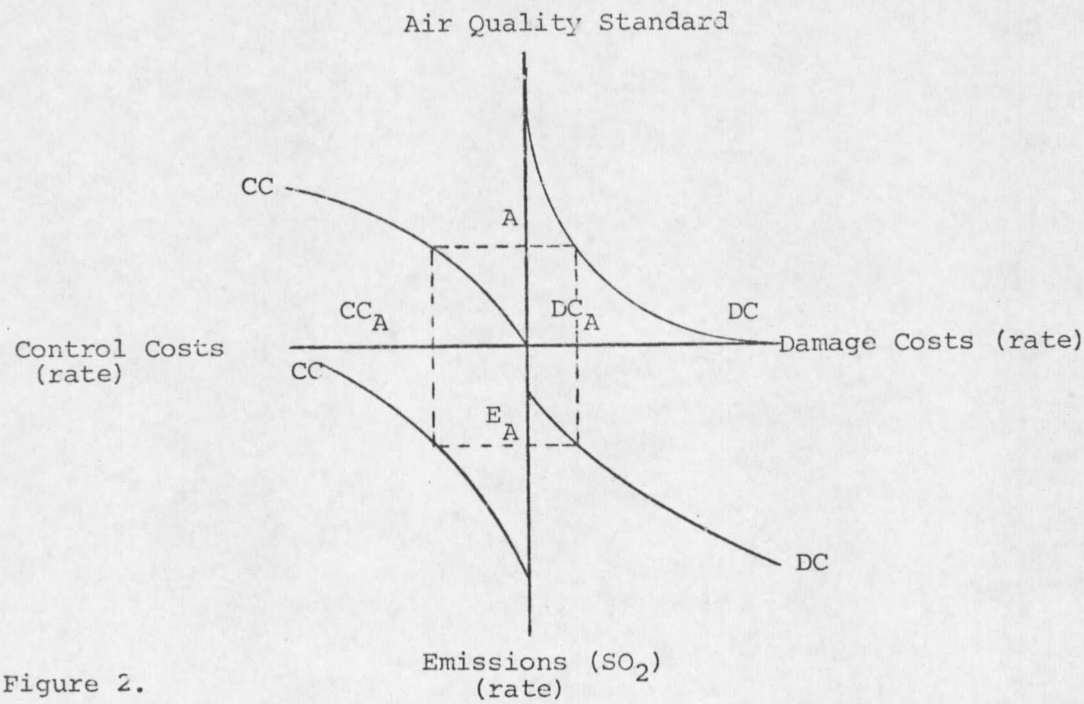

Figure 2.

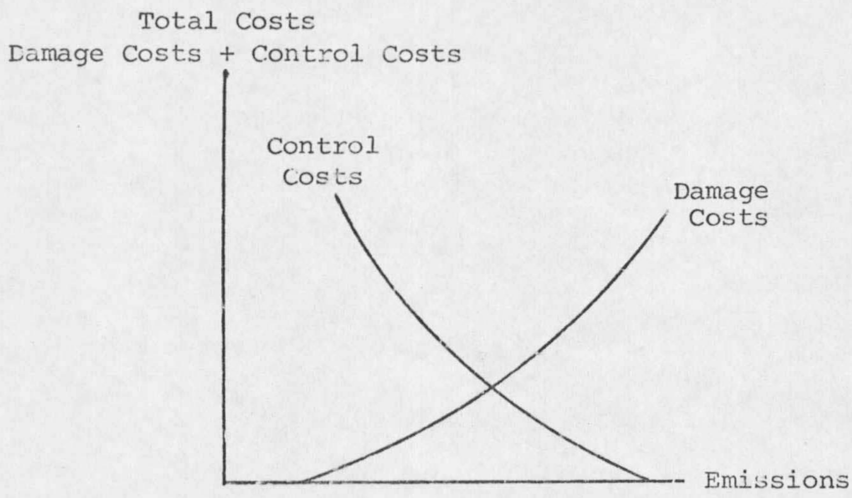

Figure 3.

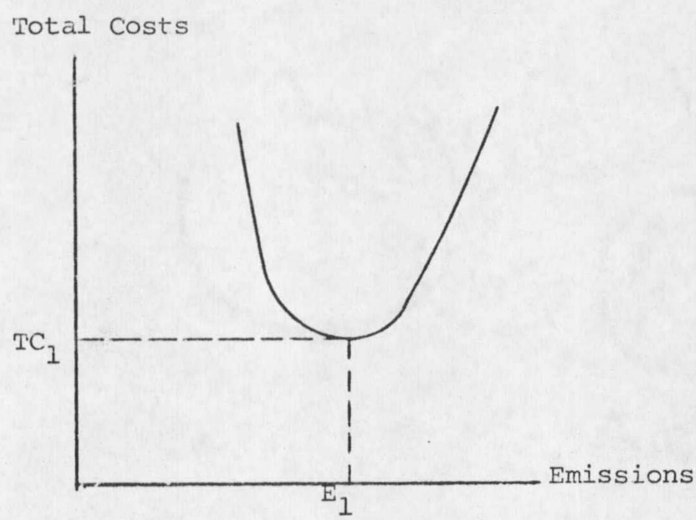

Figure 4.

Mathematical

Economic analysis indicates that marginal damage costs of pollution must equal the marginal costs of pollution control in order to achieve minimum cost quality objectives. Specifying both as a function of emissions,

$$DC_i = d_i(E) \tag{3-1}$$

and

$$CC_j = c_j(E) \tag{3-2}$$

where: DC_i = cost of the i^{th} type of pollution damage, $i = 1, n$

CC_j = cost of the j^{th} type of control, $j = 1, m$; and

E = emissions.

The total cost to society, TC, become the sum of equations (3-1) and (3-2):

$$\begin{aligned} TC &= DC_1 + DC_2 + \ldots + DC_n + CC_1 + CC_2 + \ldots + CC_m = \\ &\quad d_1(E) + d_2(E) + \ldots + d_n(E) + c_1(E) + c_2(E) + \ldots + c_m(E) \end{aligned} \tag{3-3}$$

Minimizing TC with respect to emissions produces the minimum cost to society and the optimum air quality objectives.

The necessary first-order conditions are

$$\frac{dTC(E)}{dE} = d_1(E) + \ldots + d_n(E) + c_1(E) + \ldots + c_m(E) = 0 \qquad (3\text{-}4)$$

and the sufficient second-order conditions are

$$\frac{d^2TCE}{dE^2} > 0 \qquad (3\text{-}5)$$

To satisfy the necessary conditions, the summation of the marginal costs of pollution control and damages must equal zero, or likewise, that the marginal costs of pollution damages equal the marginal costs of pollution control. That is,

$$\frac{dTC}{dE} = \sum_i \frac{d_i(E)}{dE_i} + \sum_j \frac{c_j(E)}{dE_j} = 0 \quad \text{so that} \quad \sum_i \frac{d_i(E)}{dE_i} = \sum_j \frac{-c_j(E)}{dE_j} \qquad (3\text{-}6)$$

The following chapters represent an empirical attempt to combine the control costs of pollution with pollution damage costs to enable decision makers to make marginal evaluations of emission control.

CHAPTER IV

STUDY AREA--EMITTERS

Problem Area

The Helena Valley in Montana has an air pollution problem (Table II). Located between the Big Belt Mountains on the north and east and the main chain of the continental divide on the west and south, the valley houses approximately 30,000 residents who are subjected to various degrees of pollution. In particular, the American Smelting and Refining Company operates a custom lead smelter, emitting quantities of sulfur dioxide to the atmosphere which substantially exceed the Ambient Air Quality Standards set for Montana and are in excess of the most lenient air standards set anywhere in the nation [38,p.3]. Government studies [38] indicate that concentrations of sulfur dioxide in excess of 15 ppm (parts per million) have been recorded near the plant, causing considerable damage to commercial crops and other vegetation.

Basically, sulfur dioxide is a colorless gas that can be tasted at concentration levels of .3 ppm to 1 ppm and can cause pungent, irritating odors at concentration levels above 3 ppm. Once in the atmosphere, sulfur dioxide is partly converted to sulfur trioxide or to sulfuric acid by photochemical or catalytic processes. In the presence of moisture, sulfur trioxide is immediately converted to sulfuric acid. The rate at which sulfur dioxide oxidizes in the atmosphere depends on factors such as residence time, amount of

TABLE II. EMISSION FROM COMBUSTION AND PROCESS OPERATIONS, HELENA, EAST HELENA, HELENA VALLEY, MONTANA (Tons Per Day Averaged Over the Year).*

		Source and Amount of Emissions									
		Industrial and Commercial					Domestic			Vehicular	
Pollutant	Total Emissions	Coal	Fuel Oil	Gas	Wastes	Process Emissions	Fuel Oil	Gas	Wastes	Gas	Diesel Fuel
Sulfur Dioxide	198.03	1.68	.001	.001	.005	196.0	.010	.001	.02	0.21	0.10
Carbon Monoxide	58.65	.2	.001	.001	0.5	2.0	.001	.001	1.8	54.0	0.15
Hydrocarbons	5.26	.07	.001	Neg	.03	Neg	.001	Neg	.11	4.7	0.35
Oxides of Nitrogen (NO_2)	5.51	1.40	.001	.30	.06	Unknown	.002	.38	.22	2.6	0.55
Particulate	22.72	5.70		.03	.09	16.0	.001	.03	.31	.30	.26
TOTAL	290.17										

*Source: Montana State Department of Health, Division of Air Pollution Control and Industrial Hygiene, "A Study of Air Pollution in the Helena-East Helena Area," October 1965-October 1968, p. 10.

moisture present, and the intensity and duration of sunlight. The presence of catalytic material, hydrocarbons, nitrogen oxides, and sorptive and alkaline materials also affect the oxidation process [70].

Plant Description

The American Smelting and Refining Company's smelter was built in 1885 and has vented to the atmosphere all by-product sulfur dioxide since that time. A brief description of the plant's operation is included here.

All incoming shipments of lead concentrates are sampled and determined for sulfur content. After being mixed with zinc residues, limestone and siliceous ore, the concentrate is pelletized to give a charge conforming to metallurgical requirements. After the pelletized charge is delivered to the sintering plant, it is mixed with return sinter and fed to one of four Dwight Lloyd's sintering machines where the sulfur content is reduced through oxidation and the charge is agglomerated into a product known as sinter. The sinter is then screened for removal of fines, which are in turn crushed and used as return sinter for blending with more fresh charge coming from the charge preparation system. Once delivered to the blast furnace, the gases from the sinter are conducted through flues to the electrostatic precipitator plant (ESP) where the dust in gases is largely removed and the cleaned gases still containing sulfur dioxides are discharged up a 400-foot stack.

Finished sinter and coke are then charged in one of two blast furnaces where they are melted and reacted to form lead bullion and slag. The molten products flow out of the furnace through a patented tapper and are separated by gravity in a brick-lined settler. The slag overflows the settler into slag pots for delivery to Anaconda's zinc fuming plant while the lead bullion is tapped into other pots for transfer to the drossing plant. Dust from the gases of the blast furnace is filtered through large woolen bags in the baghouse. Cleaned gases are then vented to the atmosphere through three baghouse stacks.[1]

The two sources of air pollution produced by the American Smelting and Refining Company, then, are the effluent gases from the ESP plant (95% of total) and the gases from the baghouse (2% of total).

The other source of SO_2 pollution in the area is the Anaconda Company's zinc fuming plant. This slag-treating plant processes the waste slag of the American Smelting and Refining Company to make a zinc oxide product. The process involves charging molten slag to a fuming furnace where a 2200°F temperature causes the zinc and lead to

[1]Plant visit to the American Smelting and Refinery Company in East Helena, Montana on October 15, 1969. Attending were: Stanley Lane, Plant Manager; K. W. Nelson, Director, Department of Environmental Science; Carl Thompson, Public Relations; Ben Wake, Director, Division of Air Pollution Control, Montana; members of the National Air Pollution Control Association.

fume off and form zinc oxide and lead oxide. Furnace gases are then cooled before passing into a large radiant cooler. Zinc oxide and lead oxide in the cooled gases are then removed by a fabric filter equipped with Dacron bags before the gases still containing sulfur dioxide are discharged into the atmosphere. The gases from these five stacks, 100 feet high, account for approximately 2 percent of the SO_2 in the area.

CHAPTER V

ESTIMATING THE DAMAGE COSTS OF POLLUTION

Household Damage Costs

The area surrounding the stack was divided into 540 sectors corresponding to each of the 36 wind directions, each sector 1 mile deep, out to 15 miles distant from the polluting stack (15 x 36 = 540).

The number of houses in each sector were found by using Highway Survey maps, which indicate the location of each house, and the 1970 U. S. Census of Population, for locating the number of houses in Helena.[1]

The additions to sulfation loadings in each sector were calculated using local weather data (three hourly observations) and a dispersion equation. Additions to pollution concentration (sulfation) resulting from stack emissions were calculated every 3 hours and summed on an annual basis for the years 1965-1969. The basic dispersion equation[2] used in the computer model[3] follows the form:

$$Chi = \frac{4.5675Q}{XU\sigma_z} \exp[.5(H/\sigma_z)^2] \qquad (5\text{-}1)$$

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[1]Bob Keck, Highway Planning Survey Superintendent, and his crew of engineers deserve special thanks for their efforts.

[2]Mr. Bruce Turner, Air Pollution Control Office, Durham, North Carolina, communicated this equation to me in a telephone conversation November 5, 1970 (see [71,p.38]).

[3]See Appendix A for description of computer model.

where: Chi = pollution concentration;

Q = emissions (2,772 grams at zero control);

X = distance from stack in meters;

U = wind speed in meters per second;

σ_z = vertical dispersion coefficient, a function of downwind distance and atmospheric stability; and

H = effective stack height in meters.

The computer model's predicted sulfation measurements were tested by comparing them with lead peroxide candle sulfation measurements taken by the Federal Government[4] in a study conducted June through November 1969, in East Helena, Montana. The lead peroxide candle is a widely used technique used for determining a sulfation rate. Although it provides no indication of short-term fluctuations it can give reasonable indications of sulfur dioxide concentrations for periods of one month duration [55,p.103].

By comparing the lead peroxide candles to the computer model's predictions, it was found the model underpredicted sulfation concentrations by about 15 percent (arithmetic mean) from 1 to 8 miles distance from the stack.[5] Government measurements of sulfation did not exceed 8 miles from the polluting stack.

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[4] Title of project: Helena Valley, Montana, Area Environmental Pollution Study. Principal investigators: The National Air Pollution Control Administration and the Montana Department of Health.

[5] See Appendix C for a discussion of how these values were determined.

The damage costs of pollution to households were found, then, using a dispersion model to estimate pollution concentration (sulfation) in each sector, the relative decreases in property value which people were willing to pay for increased sulfation as determined by Ridker's study,[6] where calculated damages to households were found by Ridker to be directly proportional to pollution concentration, and the number of houses in each sector. An interest rate of 6 percent was used to convert present value to annual costs.

Damage costs, then, follow the form:

$$DC = X_i H_i R E \qquad (5\text{-}2)$$

where: X_i = the increment of pollution concentration from the large stack (annual average) in the i^{th} sector with no control;

H_i = the number of dwellings in the i^{th} sector;

R = the annual damage per unit of pollution concentration per dwelling (Ridker)[7]; and

E = the proportion of generated pollutants which are emitted.

Table III and IV present the results.

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[6] See Chapter II, where it was noted that Ridker found that people did pay approximately \$245 more for a house for each .25 $mgSO_3/100\ cm^2$/day (annual average sulfation) avoided in St. Louis in 1960.

[7] The use of Ridker's value data is virtually a necessity, as no other data, comprehensive in scope of damages and considering SO_2 specifically, is currently available.

TABLE III. ANNUAL HOUSEHOLD DAMAGE COSTS (100% Emissions).

Year	Household Damage Costs a	Household Damage Costs b
	--------Dollars-----	
1965	31,922	22,302
1966	30,772	19,929
1967	33,720	24,260
1968	33,570	19,946
1969	32,600	21,200

[a]Calculated costs stemming from a sulfation rate adjusted to empirical data. Figure C-4 in Appendix C indicates the adjustments.

[b]Calculated costs stemming from an unadjusted model.

TABLE IV. AVERAGE ANNUAL HOUSEHOLD DAMAGE COSTS AT 6 DISCRETE LEVELS OF CONTROL (100% Emissions).

Control Level	Household Damage Costs [a]
Percent	Dollars
45	17,220
78	4,270
88	3,046
90	2,321
93	1,347
99.4	186

[a]Calculated costs stemming from a sulfation rate adjusted to empirical data. Figure C-4 in Appendix C indicates the adjustments.

Damage Costs to Agriculture

The following discussion describes the procedures by which damages (yield reduction) to alfalfa and barley is calculated. A basic outline is included to acquaint the reader with the order of terms which follow.

Basic Outline

I. Yield reduction is a function of leaf damage.

A. Leaf damage is a function of the absorption rate of the plant, A; concentration level of pollutant, C; and duration of fumigation, T.

a. A is a function of light intensity, soil moisture, temperature, and relative humidity.

b. C is calculated using a dispersion equation that includes emissions from the stack and effective stack height as constants. Variables include horizontal and vertical dispersion coefficients which depend on stability conditions and downwind distance from the source; windspeed and a cross-wind distance variable y which depends on changes in wind direction.

c. T is a variable time interval over which C is constant.

Recalling from Chapter II that reduction in yield is proportional to the amount of leaf area destroyed,

$$YR = f(LD) \tag{5-3}$$

where: YR = yield reduction;

LD = leaf damage.

An equation was formulated to predict leaf damage from the work of Thomas and Hill (67,p.299-300) which follows the form:

$$LD = \frac{TCA - 610 - 155T}{14.3 + 15.4T} \tag{5-4}$$

where: LD = leaf damage;

T = time (duration of fumigation);

C = concentration level of pollutant; and

A = absorption rate of the plant.

Procedures to estimate the absorption rate of the plant, the concentration level of pollutant, and the duration of fumigation are discussed in turn.

Absorption Rate of the Plant

The absorption rate of the plant depends on a number of environmental factors, including light intensity, soil moisture, temperature, and relative humidity. The model formulated in this study assumed damage to plants would only take place in daylight hours, adequate soil moisture, and daytime temperatures above 40°F. When these conditions are favorable for damage, relative humidity becomes the crucial variable of plant susceptibility to sulfur dioxide. O'Gara [42] recognized the importance of relative humidity by specifying a quadratic equation which gave the relative sensitivity of plants at different air humidities. This equation was confirmed by Thomas, Hendricks and Hill [68]. Table IV gives solutions to the equation.

TABLE IV. RELATIVE SENSITIVITY OF PLANTS TO INJURY BY SULFUR DIOXIDE AT DIFFERENT ATMOSPHERIC RELATIVE HUMIDITIES.*

Relative Humidity	Relative Sensitivity
Percent	Percent
100	100
80	89
60	77
50	69
40	54
30	31
20	18
10	13
0	10

*Source: O'Gara, P. J., "Relative Sensitivity of Cultivated and Native Plants to Injury by Sulfur Dioxide," Magil, _et al._ (Eds.), _Air Pollution Handbook_, 1956.

The variable A, then, becomes a measure of the absorptive rate per unit (dry) weight of the leaves and is mathematically independent of the duration and intensity of fumigation. The data collected by Thomas and Hill revealed that A ranged from a minimum of 30 to a maximum of 650 in their different daylight experiments. The dimensions of A were so chosen that when duration of fumigation was expressed in hours and concentration of SO_2 in the air by parts per million by volume, the absorption was given as parts per million of the dry leaf tissue [67,p.302]. Using 100 percent relative humidity as representing maximum sensitivity of plants to injury, the absorption rate was estimated by multiplying relative humidity by 650, i.e., a relative humidity of 100 percent = 1.0.

Pollution Concentration and Fumigation Duration

Calculating pollution concentration (C) and fumigation duration (T) for a receptor field in a given wind direction required a dispersion model which would reflect varying pollution concentrations with changes in wind direction. As wind changed from its initial direction, the center of the plume would move away from the receiving field and the field would suffer smaller concentration levels of pollution. The dispersion model used was of the form:[7]

$$C = \frac{Q}{\pi \sigma_y \sigma_z U} \exp[-.5(y/\sigma_y)^2] \exp[-.5(H/\sigma_z)^2] \qquad (5\text{-}5)$$

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[7]From U. S. Department of Health, Education and Welfare, Public Health Service, Workbook of Atmospheric Dispersion Estimates, Pub. No. 999-AP-26, Revised 1969, p. 7.

where: C = concentration level of pollutant;

Q = emissions;

π = 3.14159;

σ_y = horizontal dispersion coefficient, a function of downwind distance and stability;

σ_z = vertical dispersion coefficient, a function of downwind distance and stability;

U = wind speed;

H = effective stack height; and

y = cross-wind distance (distance in meters from plume centerline).

Cross-wind distance, y, reflects the distance of plume centerline from a receptor field, where increasing distance results in a decreasing pollution concentration. By calculating y and relating it to a time interval, pollution concentration and fumigation duration could then be estimated.

A computer program was written (see Appendix B) which would estimate cross-wind distance y resulting from changes in wind direction. By using the formula for arc length,

$$AL = \frac{\pi r}{180} \theta^\circ \qquad (5\text{-}6)$$

where: AL = arc length in meters;

π = 3.14159;

r = distance in meters from pollution emitter to receptor field; and

θ = the difference between original wind direction in degrees and the new wind direction in degrees.

the arc length (cross-wind distance = y) could be found for a change in wind direction (θ°).

Assume, for example, the receptor field to be 1 mile from the polluting stack and in the 90° wind direction. If the wind blew in the 90° direction continuously, the given field would receive center-line plume concentrations. The cross-wind distance variable y in the dispersion model would be assigned the value zero and a pollution concentration would be calculated using the simplified dispersion model

$$C = \frac{Q}{\pi \sigma_y \sigma_z U} \exp[-.5(H/\sigma_z)^2] \qquad (5\text{-}7)$$

If, however, the field was fumigated half the time by a wind in the 95° direction, the field would suffer less than center plume line concentration levels, and equation (5-6) used in Appendix B would be used to calculate y for use in dispersion equation (5-5).

A Rustrak recorder was used to provide continuous wind direction data which was collected in Bozeman by the meteorologists at Montana State University. Employing sensitive graph paper moving an inch an hour, the recorder indicates wind direction every 2 seconds. Wind speed in mph was averaged for each hour so that a constant wind-speed was thus assumed for each of the 1,800 wind directions for that hour. Each hour of data was then partitioned using the arbitrary rule of minutes it takes for the wind to move one-half mile.

Wind direction data of wind speeds equalling 5 miles per hour, for example, were partitioned into 6-minute intervals (the time it takes for wind moving at that velocity to move one-half mile); 6 miles per hour into 5-minute intervals; and so on to wind speeds of 12 miles per hour into 2.5-minute intervals. If the wind speed was 5 miles per hour, the hour's wind direction data were partitioned into 10 intervals, with 180 wind directions in each interval. Wind direction was then averaged for each interval.[8]

An array of the above averages was then obtained for each wind speed representing wind direction in degrees. For example, 280°, 278°, 272° ... for a wind speed of 5 miles per hour indicated a wind direction of 280° for 6 minutes, 278° for 6 minutes, 272° for 6 minutes, and so on for the remainder of the data for that hour. Using these wind direction data for each wind speed in a computer program (see Appendix B) produced estimates of the cross-wind distance, y, for each of the time intervals. Pollution concentration was then calculated for that

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[8]Wind speed of less than 4 miles per hour and greater than 12 miles per hour were omitted. Basically, wind speeds of less than 4 miles per hour exhibited such variability that a receptor field would seldom receive fumigation durations sufficient enough to cause plant damage. Wind speeds of greater than 12 miles per hour, on the other hand, would not produce high enough levels of pollution concentration to cause plant injury. Exceptions will be discussed below.

particular wind speed for each 1-mile sector from the polluting stack. This was then repeated for each of three 1-mile segments.

Pollution concentration and fumigation duration was then plotted, for each of a number of combinations of miles from the polluting stack, stability conditions, and wind speed. Figure 5 illustrates the procedure.

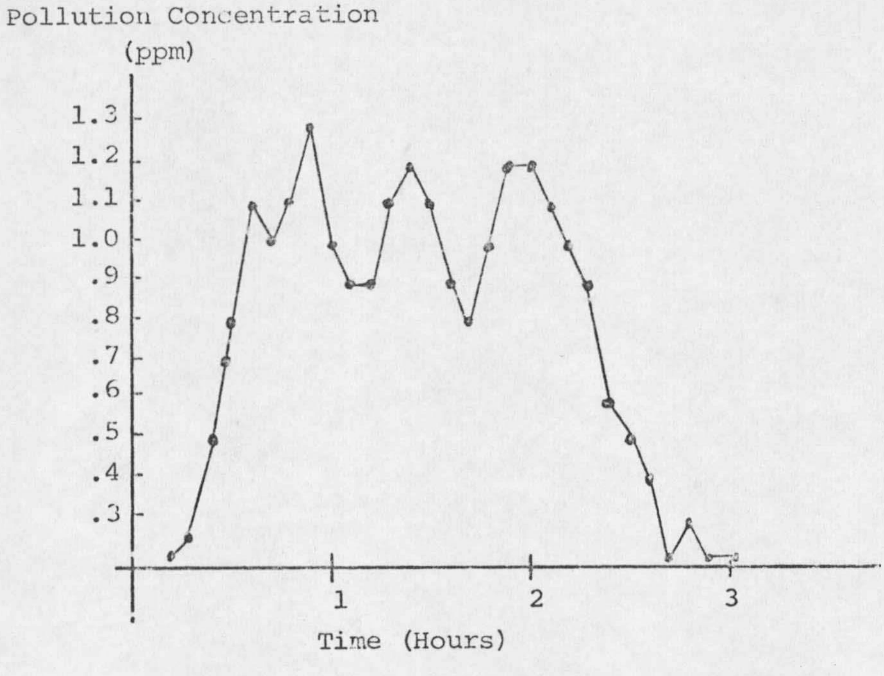

Figure 5. Pollution Concentration Given a Wind Speed of 5 Miles per Hour, a Downwind Distance of 3 Miles from the Source, and an Unstable Stability Condition.

Notice first in Figure 1 that for a wind speed of 5 mph the distance between any two points represents 6 minutes. In this example, 30 points were calculated and plotted, each representing a pollution concentration of 6 minutes duration and in total a period of 3 hours. Each graph was examined and average pollution concentrations during specific periods of time were estimated visually. In this example, a pollution concentration of one ppm was chosen for the 2-hour interval from .5 to 2.5 hours. Since research has indicated that a plant can withstand .3 to .5 ppm indefinitely without sustaining any leaf damage, concentration levels of pollutant between zero and 0.5 hours and between 2.5 and 3 hours were treated as zero in any calculations of leaf damage.

A minimum of 5 and a maximum of 10 graphs[9] were plotted for each combination of wind speed, distance from the polluting stack, and stability condition, from which average pollution concentration C for each T was estimated from each graph. Estimates of pollution concen-

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[9] Recall that each pollution concentration C was calculated using a different cross-wind distance variable y and that each y was the result of wind direction averaged for a specific interval depending on wind speed. Wind speeds of 12 mph, for example, required direction averages for 72 intervals for a 3-hour period, each interval 2.5 minutes duration. Approximately 350 intervals were averaged for each wind speed, yielding enough data for five 3-hour graphs at wind speeds of 12 mph and ten 3-hour graphs for wind speeds of 5 mph. The writer recognizes the limited data plotted and suggests refinements and mechanization for future work.

tration and fumigation duration ranged from an average pollution concentration for the entire 3-hour period to three or four average pollution concentrations, each with fumigation durations whose total was 3 hours. Figure 6 presents another illustration of the discussion.

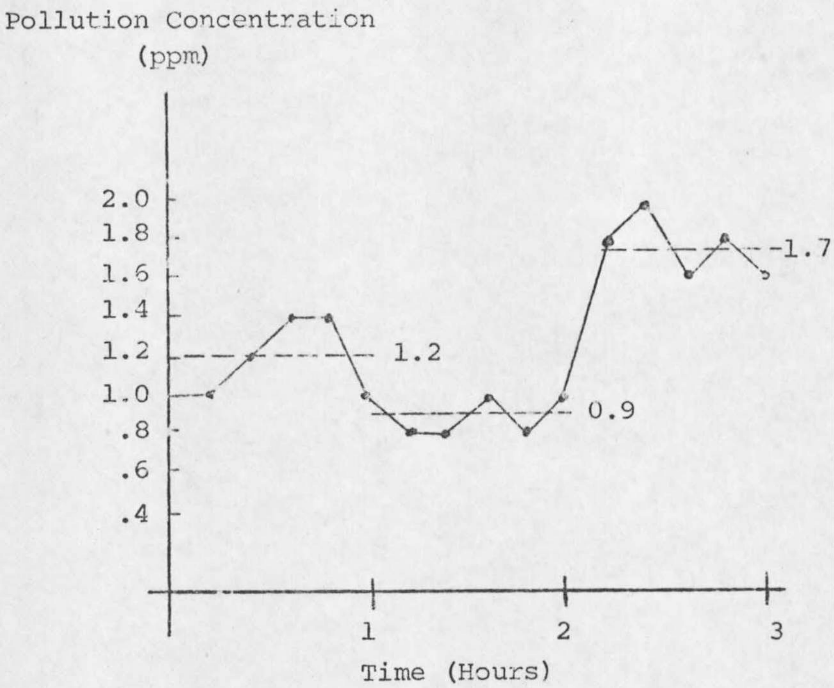

Figure 6. Estimating Pollution Concentration and Fumigation Duration.

This data, for example, was plotted, visually inspected and estimated for pollution concentrations C of 1.2, 0.9, and 1.7 ppm each of 1 hour duration. Combining each C and its T with an absorption rate of the plant A, leaf damage was calculated for each hour of the 3-hour period. Total leaf damage for each graph representing a 3-hour period was then calculated, and by adding the leaf damages for all calculated under the same conditions and dividing by the number of 3-hour periods, a mean (average) leaf damage was found and used to calculate yield reduction for each set of conditions. Please note that the graphs were averaged visually and therefore no claim is made for a completely accurate prediction of leaf damage. If a computer routine had been devised, slightly different results might have been produced.

Calculating Yield Reduction

The following equations were then used to predict yield reduction as a percentage of total crop yield by using leaf damages calculated above. Since alfalfa does not exhibit a stage of growth effect [28,66], equation (5-3) becomes, for all stages of growth

$$Y = 100 - .302X \qquad (5\text{-}8)$$

where: Y = percent of total yield;

X = percentage leaf damage (i.e., 10% = X = 10).

For barley, which does suffer greater damages with increasing growth, the following coefficients were used to estimate loss in yield [8].

$$\begin{array}{lll} Y = 100 - .00X & \text{1st - 6th week} & \\ Y = 100 - .20X & \text{7th - 9th week} & (5\text{-}9) \\ Y = 100 - .35X & \text{10th - 14th week} & \end{array}$$

The average annual yield of alfalfa and barley in each sector, assuming no pollution, was determined using data supplied by the Helena Valley Irrigation Project. Alfalfa was assumed to yield 2 tons per acre at $23.50 a ton, and barley was assumed to produce 40 bushels an acre at 85 cents a bushel. Each fumigation, coupled with the right environmental factors, would reduce the total yield attributable to that sector as discussed above.

Table V depicts the average annual damages to alfalfa and barley for all sectors given emission levels ranging from 100 percent to 50 percent.

TABLE V. AVERAGE ANNUAL DAMAGE COSTS TO ALFALFA AND BARLEY FOR YEARS 1965-1969.

Emission Level Percent	Alfalfa	Barley	Total
	-----------	Dollars	-----------
100	2,006	494	2,500
95	1,660	392	2,052
90	1,444	273	1,717
80	1,230	161	1,391
70	1,034	105	1,139
60	742	59	801
50	491	14	505

A curve was fitted to the cost estimates of varying emission levels using least squares regression analysis which took the form:[10]

$$ADC = .0203 + .081E - .105E^2 + .0468E^3$$

where: ADC = agricultural damage costs;

E = emission levels (100% = E = 1.0)

[10] ADC is in millions of dollars.

CHAPTER VI

ESTIMATING THE CONTROL COSTS OF POLLUTION

Attempts have been made to control sulfur oxide emissions for the last 150 years [51]. High costs of control as well as the fact that the costs of not controlling emissions are mainly external to the emitter have generated little volition on the part of emitters to purchase control equipment. When economic conditions or pollution control regulations do warrant control, sulfur dioxide has been recovered as sulfuric acid or elemental sulfur.

Recently a cheaper way to convert polluting oxides to elemental sulfur was announced by E. Van Dornick, whose process would rid the gas of 90 percent of its sulfur content at a cost of $5 per ton.[1] The process is now being tested and preliminary results are now becoming available. In correspondence with Van Dornick, he estimated the capital cost of the process plant for the American Smelting and Refining Company in East Helena to be $11 million and the operating costs to be $5 to $6 per ton of elemental sulfur product. Unfortunately for potential users of this process, the price of elemental sulfur has fallen from $38 a ton in 1968 to under $10 a ton presently.[2]

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[1]A description of the sulfur dioxide pollution reduction process by E. Van Dornick can be obtained by writing the Chemical Technology Corporation, 9400 Whitmore Street, El Monte, CA 97131.

[2]Wall Street Journal, November 9, 1970, p. 18.

A planned 60 percent increase in flue gas concentration by AS&R would reduce the capital costs of the process plant to $7 to $8 million.[3] Assuming, then, a capital cost of $8 million, operating costs of $5.50 per ton, and the production of 42,000 tons of elemental sulfur per year, Table VI reveals the market price of sulfur which would have to be received for a breakeven control cost.

TABLE VI. MARKET PRICES OF ELEMENTAL SULFUR NEEDED TO FORCE CONTROL COSTS TO ZERO GIVEN THREE RATES OF INTEREST USED TO CONVERT CAPITAL COSTS TO ANNUAL COSTS.

(1970)

Interest Rate	Capital Cost	Operating Cost	Total Cost	Market Price of Sulfur	Control Costs
Pct.	---Millions of Dollars--			------Dollars------	
10	.80	.23	1.03	24.52	0.00
6	.48	.23	.71	16.88	0.00
3	.24	.23	.47	11.19	0.00

The process plant is based on a 90+ percent SO_2 removal and a 95+ percent elemental sulfur recovery. Essentially all of the particulates can be conveniently removed either by the process equipment alone or with nominal auxilliary facilities. The process is designed specifically for a 90+ percent SO_2 removal and is a 95+ percent operation. Van Dornick explains that the process could not be operated at lower levels of recovery or SO_2 removal.

[3]This information was communicated to me by E. Van Dornick in a letter dated September 28, 1970.

Minimum cost control methods of more conventional design for the AS&R lead smelter under consideration were furnished by the Environmental Protection Agency.[4] Cost data for control of a Dwight Lloyd sintering machine were given that would result in the lowest cost per ton of sulfur removed for the control level specified. Basic assumptions used to derive the capital and operating costs for various levels of control efficiency are explained as follows.

Investment and operating costs were taken from the Systems Study for Control of Emissions: Primary Nonferrous Smelting Industry, by Arthur G. McKee and Company, June 1969.[5] A 15-year straight-line depreciation, with interest costs at 10 percent, and administration costs of 3 percent, were used for calculating annual capital costs. A credit of $5.35 per ton of recovered acid was assigned wherever applicable. At the 99.4 percent control level, the smelter's operator is assumed to purchase reactive lime for $4 per ton rather than invest in a lime kiln and produce the material. This assumption is valid because of the small quantity of lime needed to treat the final 7 percent of waste sulfur dioxide. The cost data are listed in Table VII.

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[4]Mr. Frank Bunyard, Environmental Protection Agency, Air Pollution Control Office, Division of Economic Effects Research, communicated the necessary information to me in a letter dated February 11, 1971.

[5]Available from the clearinghouse for Federal Scientific and Technical Information, U. S. Department of Commerce, Springfield, Virginia.

TABLE VII. COST DATA FOR SULFUR EMISSION CONTROL.*

Control Efficiency	Percent 45	78	88	93	99.4
1. Capital Cost ($ million)					
a. Limestone grinder	.7	1.1			
b. Lime kiln			2.9		
c. Scrubber & waste treatment	1.1	1.2	1.2		1.3
d. Contact acid plant				8.4	8.4
Total Capital Cost	1.8	2.3	4.1	8.4	9.7
2. Annual Operating Cost ($ million)					
a. Annual capital costs	.36	.46	.83	1.68	1.94
b. Operating & maintenance costs	.46	.82	1.05	1.37	1.60
c. By-product credits				(.80)	(.80)
Total Operating Costs	.82	1.28	1.88	2.25	2.75

*Source: Mr. Frank Bunyard communicated the information in this table to me in a letter date February 11, 1971.

Least squares regression was used to fit a curve to the five data points for the various emission levels which took the form:

$$CC = -2.97 + 6.311 * e^{(-E)}$$

where: CC = control costs;

E = emissions.

A linear fit was suggested by Mr. Bunyard for control efficiencies between 0 and 45 percent control. The fit for this linear relationship took the form:

$$CC = -2.22E - 1.$$

CHAPTER VII

SENSITIVITY OF RESULTS TO PARAMETER CHANGES

> In the search for ways to improve the misallocation [of resources] resulting from external effects, care must always be exercised to take into account any additional costs or penalties associated with the remedy. It is quite possible, for example, to set standards designed to reduce external effects so strict that there will be a loss to national product rather than a gain [26,p.9].

Estimates of the social costs of pollution and control, although difficult, must be made for rational control policies. These estimates are reviewed here for purposes of analysis, enabling authorities to make better decisions because of increased information.

Under the assumption that Ridker's value data do not fully capture the disbenefits associated with SO_2, the average annual household damage costs of $33,000 listed in Table III were doubled.[1] Adding average annual agricultural damage costs of $2,500 (Table V), total

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[1]Recall that damages per household were estimated using Ridker's St. Louis study where people there paid $245 more for a house for each .25 mg SO_3/100 cm^2/day avoided. At 6 percent interest, $245 represents about $1.20 per month per household. Ridker's value data estimate only household damages. Since damages occur to people <u>and</u> property, the somewhat arbitrary assumption was made to double the damages calculated by using Ridker's numbers to capture total damages.

pollution costs were estimated to be $68,500. Total annual costs, including control, agriculture, and household, can then be summarized by

$$TAC = -2.22E + 2.22 - .0203 + .081E - .105E^2 + .0468E^3 + .066E$$

where: TAC = total annual costs;

E = emissions (100% = 1.0);

$-2.22E + 2.22$ = control costs[2];

$-.0203 + .081E - .105E^2 + .0468E^3$ = agricultural damage costs;

$.066E$ = household damage costs.

All cost figures are in millions of 1971 dollars.

If the socially desirable amounts of pollution control are assumed to be the least costly combination of means available, the level of pollution sought should be the point where the cost of a further reduction would just exceed the benefits. Given the damage costs estimated in this study and the control possibilities estimated by the Environmental Protection Agency, there is no level of

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[2]The linear control cost function is included here where an interest rate of 10 percent was used to convert capital costs to annual costs. Least squares regression analysis was used to fit a curve to the five discrete control costs estimated by NAPCA taking the form $C = -2.97 + 6.311 * Exp^{(-E)}$. C represents costs and E represents emission levels.

control which can presently be justified on efficiency grounds. Although substantial damages have been estimated, the total cost function is minimized at 100 percent emission levels and a total cost of $68,500. Table VIII shows the pollution and control costs for seven discrete points of control and for changes in the basic assumptions. An asterisk (*) indicates the control levels necessary to minimize costs given various assumptions about the data.

The first line in each set of assumptions indicate a zero level of control. Lines 2 through 6 indicate the control costs estimated by EPC for five discrete control levels. Line 7 gives the control cost estimates by E. Van Dornick (EVD) for the 90 percent control level. The basic assumption, B, indicates a doubling of household damage costs estimated using Ridker's value data. Ten, 6 and 3 percent indicate the rate of interest used to convert capital costs to annual costs.

Control cost estimates for E. Van Dornick's 90 percent control method are estimated as follows. The basic capital cost is converted to annual costs by the appropriate interest rate. The plant is capable of producing 42,000 tons of elemental sulfur per year at an operating cost of $5.50 per ton. Assuming the market price of sulfur to be $9 per ton, $378,000 are then subtracted from the plant's total annual operating and capital costs to yield the annual control cost estimates.

Assumptions 1, 2, and 3 indicate that total costs would be minimized at 0 percent control levels given the basic assumption B

TABLE VIII. THE DISCRETE CASE CONTROL COSTS ESTIMATED BY EPC AND E. VAN DORNICK (EVD). (All Costs are in Annual Terms)

Change in Assumptions	Emissions	Control Level	Control Costs	Agricultural Damage Costs	Household Costs	Total Costs
		Pct.	------Millions of Dollars------			
1. B (10%)						
	1.0	0	0.00	.0025	.0660	.0685*
	.55	45	1.00	.0002	.0172	1.0172
	.22	78	1.51	.0000	.0043	1.5143
	.12	88	2.29	.0000	.0030	2.2930
	.07	93	3.09	.0000	.0013	3.0913
	.006	99.4	3.72	.0000	.0001	3.7201
EVD	.1	90	.652	.0000	.0023	.6543
2. B (6%)	1.0	0	0.00	.0025	.0660	.0685*
	.55	45	.928	.0002	.0172	.9452
	.22	78	1.418	.0000	.0043	1.4223
	.12	88	2.126	.0000	.0030	2.1290
	.07	93	2.754	.0000	.0013	2.7513
	.006	99.4	3.332	.0000	.0001	3.3321
EVD	.1	90	.332	.0000	.0023	.3343
3. B (3%)	1.0	0	0.00	.0025	.0660	.0685*
	.55	45	.874	.0002	.0172	.8912
	.22	78	1.349	.0000	.0043	1.3533
	.12	88	2.003	.0000	.0030	2.0060
	.07	93	2.502	.0000	.0013	2.5033
	.006	99.4	3.041	.0000	.0001	3.0411
EVD	.1	90	.092	.0000	.0023	.0943
4. 20B (10%)	1.0	0	0.00	.0025	1.3200	1.3225
	.55	45	1.00	.0002	.3440	1.3440
	.22	78	1.51	.0000	.0860	1.5960
	.12	88	2.29	.0000	.0600	2.3500
	.07	93	3.09	.0000	.0260	3.1160
	.006	99.4	3.72	.0000	.0025	3.7225
EVD	.1	90	.652	.0000	.0460	.6980*

(table continued)

TABLE VIII. (continued)

Change in Assumptions	Emissions	Control Level	Control Costs	Agricultural Damage Costs	Household Costs	Total Costs
		Pct.	------Millions of Dollars------			
5. 20B (6%)	1.0	0	0.00	.0025	1.3200	1.3200
	.55	45	0.928	.0002	.3440	1.2180
	.22	78	1.418	.0000	.0860	1.4350
	.12	88	2.126	.0000	.0600	2.0630
	.07	93	2.754	.0000	.0260	2.7800
	.006	99.4	3.332	.0000	.0025	3.0735
EVD	.1	90	.332	.0000	.0460	.1380*
6. 20B (3%)	1.0	0	0.00	.0025	1.3200	1.3200
	.55	45	0.874	.0002	.3440	1.2720
	.22	78	1.349	.0000	.0860	1.5040
	.12	88	2.003	.0000	.0600	2.1860
	.07	93	2.502	.0000	.0260	2.5280
	.006	99.4	3.041	.0000	.0025	3.3345
EVD	.1	90	.092	.0000	.0460	.378*
7. B (7%)	1.0	0	0.00	.0025	.0660	.0685*
EVD	.1	90	.413	.0000	.0023	.4153
8. 7B (7%)	1.0	0	0.00	.0025	.4620	.4645
EVD	.1	90	.413	.0000	.0161	.4291*
9. B (7%)	1.0	0	0.00	.0025	.0660	.0685
EVD	.1	90	.056	.0000	.0023	.0583*

and for interest rates of 10, 6, and 3 percent. The market price of elemental sulfur would have to be $23,00, $15.42, and $9.72 for assumptions 1, 2, and 3, respectively, before EVD would become a minimum cost solution.

Multiplying household damage costs by 20(20B) as shown by assumptions 4, 5, and 6, indicates that minimum cost solutions would involve zero control for the cost figures estimated by EPC. Excluding Van Dornick and using the lowest discrete control level destimated by EPC, the basic estimate of damage costs would have to be increased by a factor of 20 before control could be justified on efficiency grounds. If damages were 20B, EVD becomes the minimum cost solution at a control level of 90 percent.

Assumptions 7 and 8 are included to indicate the viability of the EVD control process as a minimum cost means of control. Using an interest rate of 7 percent[3] and a market price of elemental sulfur of $9[4], the conclusions are as follows. Given the basic assumption,

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[3]The money rate of interest was determined by checking the corporation bond market in the July 23, 1971 Wall Street Journal for the American Smelting and Refining Company. Showing a coupon value (contract rate of interest) of 4 5/8, a $1,000 bond was selling for $705, maturing in 17 years. By examining the present value of $1,000 due in 17 years and the present value of annuity of $42.63 received at the end of each year, a money rate of interest of 7 percent was determined.

[4]Price of a long ton of elemental sulfur f.o.b. Alberta, Canada July 23, 1971.

B, no control can be justified as shown in assumption 7. Assumption 8 indicates that the basic estimate of damages would have to be increased by a factor of 7 before EVD minimizes costs. Assumption 9, indicates the market price of sulfur would have to be approximately $17.50 before EVD becomes the minimum cost solution.

Comments on Results

Conclusions other than those reported in this study would be warranted given the following possibilities. First, damage costs may be significantly underestimated. Second, control methods less costly than those reported may become available. And finally, the alternative of plant shutdown as a control alternative is a possible solution.

Imperfect information about the pollutant's effect on health, vegetation, and materials, a lack of certainty in the diffusion model, and the possibility of an increased effect (synergism) by a chemical recombination once airborne, could all affect estimates of damage costs.

The damage costs calculated in this study are probably underestimates.

Care was taken to adjust annual sulfation rates by a conservative factor of 10 percent, and though damages could occur at annual sulfation levels below .49 mg $SO_3/100\ cm^2/day$, all damages below this level were excluded.

This was consistent with Ridker's study of using .49 mg as a background level. In addition, the harmful effects of intermittant high level concentrations of sulfur dioxide were not estimated.

Estimated damages to agriculture were also minimum. Although the relevant research indicated differences of opinion regarding damages to alfalfa and barley during night hours, damages were estimated only during daylight hours. Abnormal weather conditions causing heavy concentration levels of pollution and/or extended fumigation durations in relatively small areas could cause significant leaf damages. Although these conditions probably inflict greater damages than those estimated, the frequency of occurrence was not known and hence not evaluated. An indication of the underestimate of crop damages is the fact that over $14,000 were paid for crop damages in 1967, 1968, and 1969 by AS&R while this study indicated damages of $7,23[illegible] for the comparable 3-year period.

Means of control less costly than those estimated by the Environmental Protection Agency (EPC) and E. Van Dornick could also alter the conclusions in this study. A representative of EPC indicated, however, that "the one control scheme that would result in the lowest cost per ton of sulfur removed for the specific control level" was used, and further, "in a practical sense, a smelter operator would choose the least-cost strategy for a given control level similar to the approach

I am presenting you."[5] Concerning the EVD control process, many engineering evaluations indicate that it is superior in simplicity and cost compared to other existing methods recovering elemental sulfur from flue gas.[6]

Another possibility would be the alternative of plant shutdown. If the basic assumptions in this study are correct then shutdown would appear to be socially efficient if expected annual rent losses to land, labor, and capital were less than $68,500. An estimate of these losses would be difficult and is beyond the scope of this study.

Implications of the Results

Damages of $68,500 are certainly not inconsequential, especially when seven-tenths of these damages occur within 1 1/2 miles of the stack. If people do have the right to clean air, equity would require that they be compensated by the amount they are damaged. Remuneration, for example, might include direct payments from AS&R to the receptors. A payment schedule appears to be an attractive alternative, both on equity and incentive grounds. First, damaged parties are compensated

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[5]Mr. Frank Bunyard communicated this information to me in a letter dated February 11, 1971.

[6]"Scientific Evaluation, Engineering and Technological Appraisal of the Van Dornick Sulfur Dioxide Reduction Process," Dr. Walter W. Walker, P.E., F.A.I.C., 729 No. Richey Blvd., Tucson, Arizona and Joseph H. Herz, Chief Technologist, California Portland Cement Co., Colton, California.

according to the costs they incur. And second, the current trend of dogmatic insistence by polluters that control mechanisms are too expensive could be reversed by creating an incentive to seek control methods which would cost less than damages paid. If the damages to receptors are known and payments enforced, the plant would continue to emit only as long as the costs from additional emissions are less than that which it would have to pay to reduce emissions.

Until cheaper control possibilities are discovered or future research indicates damages presently unaccounted for, the gain in efficiency by better social control decisions at this plant appear to be negligible. Further research on the significant parameters in this study as they apply to this plant of the American Smelting and Refining Company, (except on the possibility of shutdown) would not appear to be warranted.

Given that receptor damages depend in part on factory location and wind patterns, it appears that this plant is suitably located. If the prevailing winds, for example, were toward the city of Helena 95 percent of the time, instead of the current 4 to 6 percent, the model indicated household damages of $4,423,000 and an emission control level of 90+ percent.

The model was also applied to the AS&R copper smelter in Tacoma, Washington, (emissions only double), where household damage costs totaled $8 million and the minimum cost solution called for 90+ percent emission control. Plant location, then, as well as emissions and control costs affect control decisions.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

A 1969 governmental study of the AS&R lead smelter in East Helena, Montana recommended that a substantial reduction in sulfur oxide was necessary and in keeping with the varying activities and economic interests of the area. Empirical guidance for determining the efficiency of a "substantial reduction" has been lacking due in part to the lack of information on pollution costs.

A computer program was written to refine and extend a methodology developed by Stroup to estimate household damage costs, while agricultural damage costs were estimated using a new methodology for calculating yield loss due to SO_2 fumigations. Combining these pollution costs with control costs estimated by EPC and Van Dornick, a total cost equation was estimated and minimized to indicate efficient levels of emission control.

The household damage costs were calculated using local weather data in a computer program written to predict annual sulfation rates, population and housing data, and the value data from a St. Louis property value study by Ridker. Agricultural damage costs were estimated by combining a dispersion model to predict pollution concentration, and a study by Thomas indicating the absorption rate of the plant, with estimates of fumigation duration using wind direction data.

The basic total cost estimate was minimized at zero control, where efficiency indicated that even if estimated damages were increased by a factor of 20 using EPC estimates or a factor of 7 using Van Dornick estimates, uncontrolled emissions were still optimal.

Substantial pollution damages were estimated, however, and if people do have the right to clean air, remuneration seems equitable.

In summary, the model presented in this paper was an attempt to give an operational answer to the hard policy questions facing decision makers. The model can be adapted to other situations as it was in Tacoma, or it can be adjusted for new numbers when new research like Ridker's becomes available.

Limitations of Study

The lack of empirical research similar to the study by Ridker makes air pollution control decisions difficult. Reasons for assuming his numbers low as applied to Montana would include the increased awareness of the environment since his 1960 study and the possibility that people who live in Montana have greater preferences for clean air. Differing supply conditions for housing of each environmental quality, between Helena and St. Louis, also could affect the applicability of Ridker's figures in Helena. Any new research made available and yielding new numbers, however, could easily be incorporated into the model.